PRODUCTION TECHNOLOGY OF A FLAT NANOFIBROUS STRUCTURE USING THE BELT ELECTRODE FOR AC ELECTROSPINNING

[1]Ondrej BATKA, [1]Jan VALTERA, [1]Josef SKRIVANEK, [1]Ondrej FRIEDRICH

[1]TUL - Technical University of Liberec, Department of Textile Machine Design, Liberec, Czech Republic, EU, ondrej.batka@tul.cz

https://doi.org/10.37904/nanocon.2022.4602

Abstract

The article deals with new technology for the production of a flat nanofibrous structure using AC electrospinning and the development of a new type of spinning electrode. Simulations of the distribution of the electric field around the electrode were performed. The dependencies of the electric field intensity on the design parameters of the electrode were determined. Based on the performed simulations, a suitable technical and technological solution of the electrode for the production of a flat nanofibrous structure was designed. The functionality of the designed technological system was verified experimentally. The results of the experiments demonstrated the high potential of the designed system for the production of flat nanofibrous structures.

Keywords: AC electrospinning, electric field, nanofibers, spinning electrode, belt electrode

1. INTRODUCTION

Electrospinning is currently one of the established methods used for the industrial production of nanofibers. Nanofiber products have the potential for application in many fields of human activity [1–5] . One type is AC-electrospinning [6, 7], which uses an alternating electric field. This principle is currently used mainly for producing narrow strips of nanofibers or for producing nanofiber yarns [8–10]. Currently, there is an effort to use AC-electrospinning to produce flat nanofiber products with large widths. This contribution deals with researching and developing an electrode suitable for creating flat nanofibrous products.

Based on successful experiments with discontinuously rewinding a textile with a polymer solution over an electrically charged edge, the aim of this task was to design a functional model of a new type of AC electrode with a continuously rewound belt. The assumption here is that the rewound belt will enable the transport of the polymer solution from the reservoir to the upper part, where nanofibers will form due to the supercritical value of the electrical intensity. The subsequent rewinding of the belt and its wading in the polymer bath ensure continuous cleaning and dissolution of any fibers on the surface of the belt. The width of the belt determines the length over which the fibers are formed, which enables the production and application of nanofibers to the underlying textile in an adequate amount and uniformity for subsequent use, e.g. in filtration, technical textiles, etc. As part of this task, based on the detailed results of the electric field simulation, a strip AC electrode including drive and gearbox was designed. The functionality of the manufactured laboratory equipment was experimentally verified, including the measurement of the specific gravity of the nanofibrous layer.

2. SIMULATION

The analysis of the electric field was used as support for the design of the optimal geometry of the electrode during the AC-electrospinning. The electric field distribution was analyzed using the finite element method in the Autodesk Simulation Mechanical software 2015. The FEM model was created as a linear 2D problem. **Figure 1 a)** shows a detailed FEM model. Its dimensions and shape correspond as closely as possible to the real model. A detailed model of the device consists of a belt electrode (steel plate, wading roller and a wound belt), a device frame, a reservoir with a polymer solution and an air environment. **Figure 1 c)** shows a simplified model that was used in the variational analysis of the strip electrode geometry. Spinning by AC electrospinning does not require the use of an oppositely charged collector, as a virtual collector is created around the electrode due to air ionization, and the charge travels to the far end with a different potential. For this reason, in the model, this virtual collector is created as an equidistant boundary around the electrode at a distance of 50 mm with a boundary condition of 0 V. A boundary condition of 25 kV was applied to the electrode and the polymer, which corresponds to the supplied electric voltage. The relative permittivity of 109 was entered for the electrode. The surrounding environment consists of air with a relative permittivity of 1. The model also contains a polymer solution with a relative permittivity of 20 and HDPE with a value of 2.3.

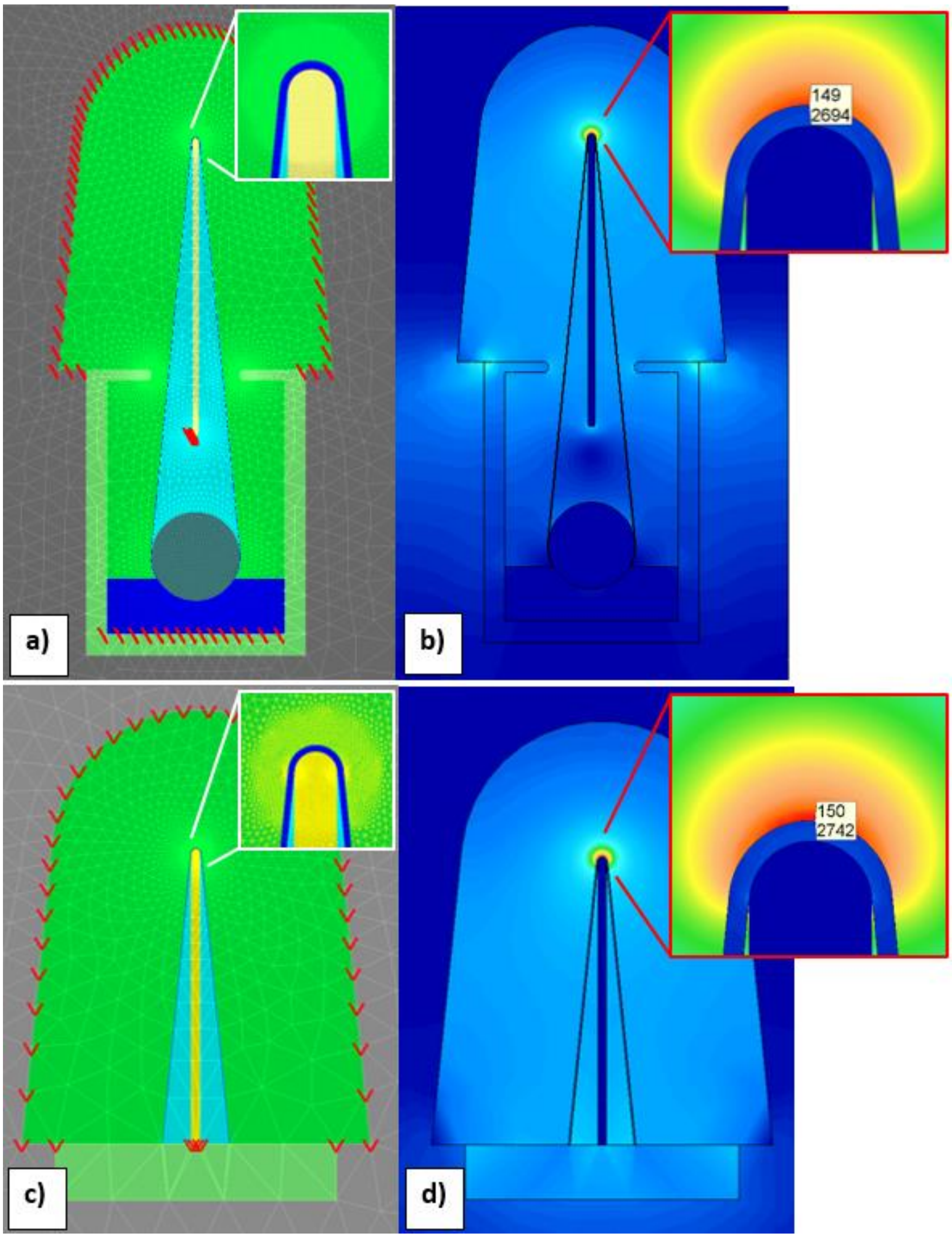

Figure 1 detailed FEM model a), electric field distribution for detailed model b), simplified FEM model c), electric field distribution for simplified model b)

The first simulation was was performed with a detailed model (**Figure 1 a)**). The goal was to determine the electric field's overall distribution in the proposed device's vicinity. A voltage of 25 kV was applied to the electrode and the polymer. **Figure 1 b)** shows this model's electric field intensity distribution. At the top of the electrode where electrospinning is desired, the magnitude of the intensity is 2694 V/mm.

The second task was performed with a simplified model whose geometry is shown in **Figure 1 c)**. This model was created due to the complexity of adjustments when changing the parameters on the first model and the speed of calculation. In the case of a simplified model with an applied voltage of 25 kV, the magnitude of the intensity on the spinning area of the electrode is 2742 V/mm, see **Figure 1 d)**. The difference between the detailed and the simplified model is slight; therefore, the simplified model was used for further analyses.

Three analyzes were performed with the simplified model. A sketch with the dimensions of the simplified model is shown in **Figure 2 a)**. Material properties and boundary conditions were used from the detailed model. During the first analysis, the electrode height parameter H was varied from 25 to 150 mm at a constant thickness t = 3 mm and radius R = 1.5 mm. The distance H is measured from the container's top to the electrode's highest part. **Figure 3 a)** shows the intensity distribution at the top of the electrode when the height H changes. At H = 25 mm, the intensity value is 2863 V/mm. As the value of height H increases, the intensity is almost constant. For further analyses, the electrode height H = 100 mm was chosen. In the second analysis, the radius R at the top of the electrode was changed from 0.25 to 2.5 mm at a constant height of the electrode H. As the radius increased, the thickness of the electrode t also increased, depending on t = 2R. Model of the top of the tip is shown in **Figure 2 b)**. The graph in **Figure 3 b)** shows the dependence of the intensity at the top of the electrode as the radius changes. At the size of the radius R = 0.25 mm, the intensity at the top of the electrode reaches a value of 4407.5 V/mm. As the radius value increases, the intensity value decreases exponentially. In the third analysis, the electrode thickness t was varied at a constant electrode height H and radius R = 0.5 mm, according to the sketch in **Figure 2 c)**. **Figure 3 c)** shows the dependence of the intensity at the top of the electrode when the electrode thickness t changes from 1 to 5 mm. At a thickness of t = 1 mm, the intensity reaches a value of 3889 V/mm. As the thickness increases, the intensity value decreases exponentially.

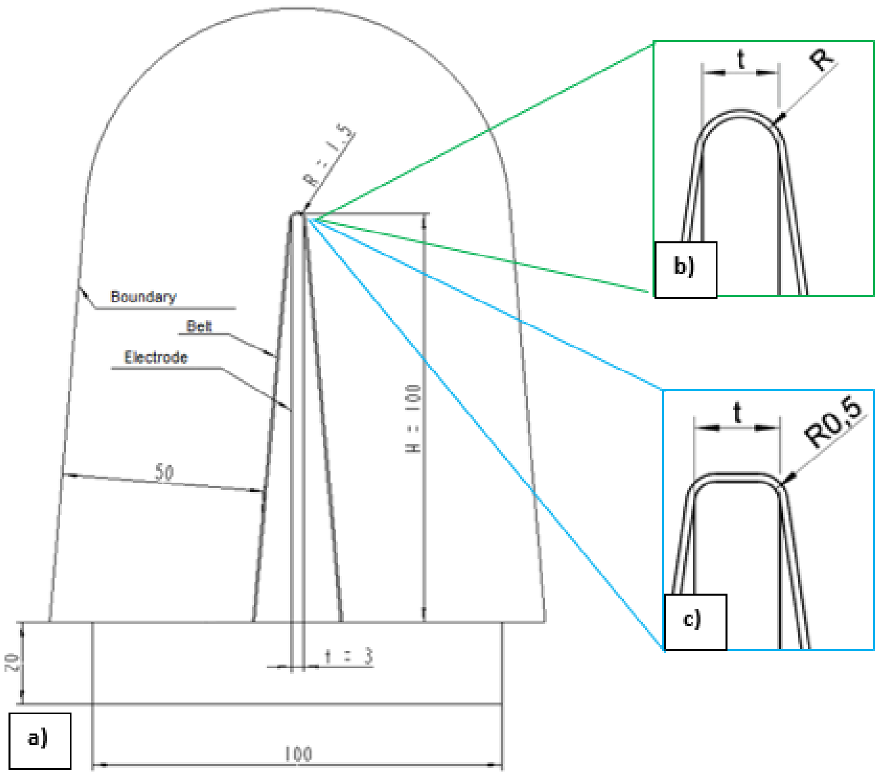

Figure 2 sketch of model

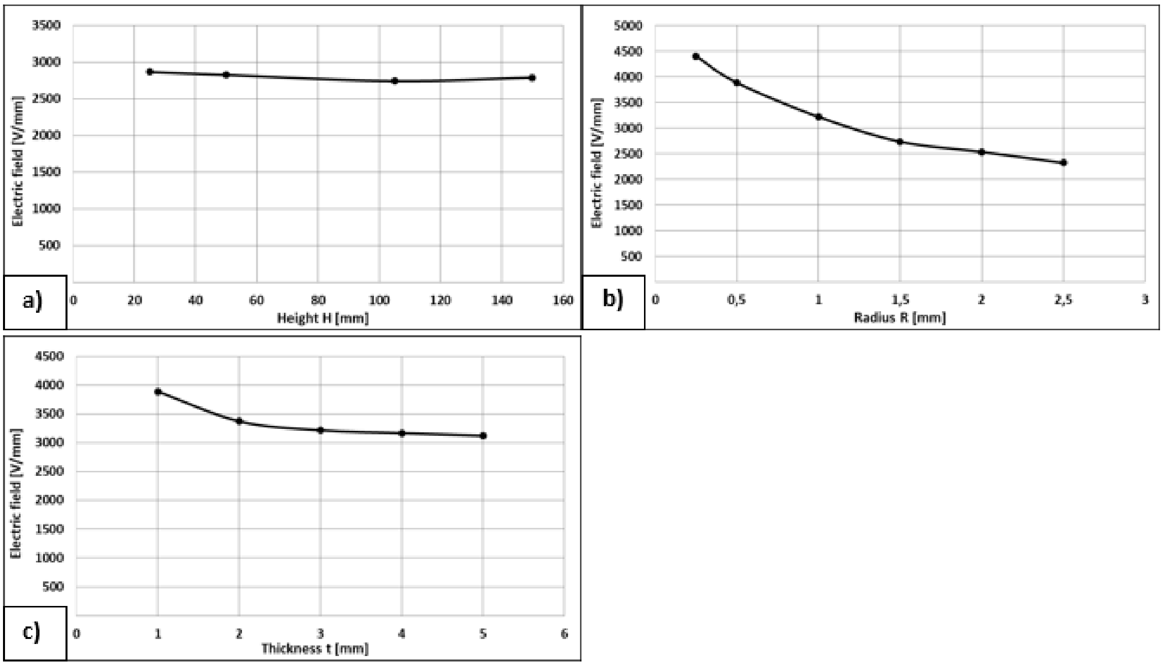

Figure 3 a) dependence of the electric field on the height of the electrode, **b)** dependence of the electric field on the radius of the electrodes tip, **c)** dependence of the electric field on the thickness of the electrode

3. DESIGN

Figure 4 shows a 3D model of a device for producing nanofibers constructed in the Creo Parametric program. An asynchronous motor with a belt transmission previously used in tests of other methods of alternating spinning was used to drive the device. The engine speed could be regulated using a frequency converter. The output speed from the belt mechanism was transmitted using a worm gear. This achieved optimal speeds and torque for driving the electrode belt. The output shaft of the worm gearbox drives the belt drive cylinder. At the same time, this shaft works as isolation of the high voltage between the AC electrode and the grounded worm gear. The belt drive ensures the shaft rotation on which the roller is mounted. The shaft is fixed using sliding bushings in the container. In the container, there is a polymer solution, without which it would not be possible to spin, as well as two drain holes equipped with screws. The movement is given to the belt through the notched roller, and the polymer is also applied over it.

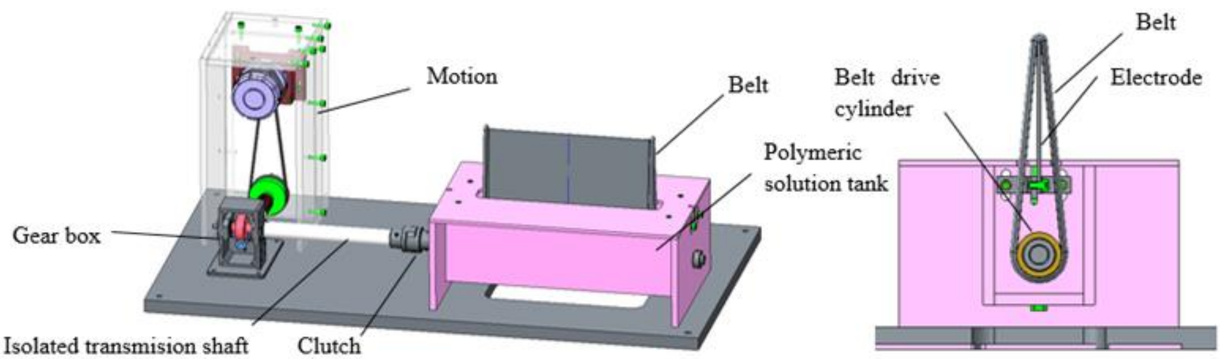

Figure 4 design of electrode

An electrode is placed above the roller, which is made of sheet metal and has a rectangular shape with rounded edges with dimensions derived from the results of the electric field simulation. During the process, a belt is moved over the upper edge of the electrode. The construction of the electrode is designed so that it can be moved vertically due to belt tension. A lid covers the electrode's frame with the polymer solution's reservoir with a hole for the belt.

4. EXPERIMENT

The designed experimental device was built and used for the experiment was carried out in order to verify the functionality of the model and whether it is possible to produce nanofibers in the required width. A polymer solution of polyvinyl butyral dissolved in ethanol was used for the experiment (10%wt PVB Movital B60H in 98%vol ethanol Technisolv). During initial tests, different belt materials were verified. First, a strip of plastic foil was tested. The problem was that the lower knurled shaft did not have enough traction on the foil and the foil also cut into the edge of the electrode. In the end, a non-woven fabric was chosen as the belt. The non-woven fabric belt easily moved over the electrode's edge and absorbed the polymer well. The produced nanofibers were applied to a rotating drum placed above the electrode. The experiment is shown in **Figure 7**.

Figure 5 experiment

Various electrode widths and thicknesses were tested. For the first experiment, an electrode with a thickness of 3 mm and a width of 240 mm was produced. At these parameters, self-spinning did not occur. For these parameters, the intensity value is 2739 V/mm (**Figure 5**). This intensity is close to the critical spinning value of 2150 V/mm, at which spinning no longer occurs. In the second experiment, an electrode with a thickness of 1 mm and a width of 240 mm was used. At these parameters, a stable spinning process was already taking place. The effort was to produce nanofibers as wide as possible. Therefore, an electrode with a thickness of 1 mm and a width of 320 mm was used for the next experiment. At these parameters, the productivity of nanofiber production was found to be 2 g*min-1*m-1.

5. CONCLUSION

This research aimed to create a model, perform analyses, design the structure and then verify it experimentally. An electrode with a height of 100 mm, a thickness of 1 mm and a radius of 0.5 mm was selected from the analysis. With these electrode parameters, the value of the intensity on the spinning area was 3889 V/mm.

Subsequently, the device's design for producing nanofibers was designed. An electrode with a width of 320 mm was used, and the productivity of nanofiber production was measured to be 2 g*min-1*m-1. This productivity can be further increased by using several electrodes in a row.

The advantage of this design is self-cleaning, when the polymer on the electrode does not dry out due to the constant wetting of the strip in the reservoir with the solution. With this design, the polymer is in the container, but it is possible to design such a design where the polymer is wiped off, and the fresh polymer is applied. The construction of the functional model is designed with an electrode width of 320 mm. Structurally, however, it is possible to design a strip electrode with a longer usable length, enabling the continuous production of flat nanofibrous material with a larger width. The disadvantage is spinning from the edges of the electrode, where as a result of higher values of the electric field intensity, there is a more intensive production of fibres and the edges of the textile are more massive. This problem, which is common in textiles, is usually solved by cutting off the edges of the textile. The fineness of the produced layer was measured from the obtained samples, which showed very good uniformity of the layer in the center and edges of the produced nanofibrous layer. A more detailed measurement of fineness and the design of a new device will be the subject of further work in this area of research

ACKNOWLEDGEMENTS

This publication was written at the Technical University of Liberec as part of the project with the support of the Specific University Research Grant 2021-5029, as provided by the Ministry of Education, Youth and Sports of the Czech Republic in the year 2021.

REFERENCES

[1] LANNUTTI, J., D. RENEKER, T. MA, D. TOMASKO a D. FARSON. Electrospinning for tissue engineering scaffolds. *Materials Science and Engineering: C* [online]. 2007, vol. 27, no. 3. Next Generation Biomaterials, pp. 504–509. ISSN 0928-4931. Available from: https://doi.org/10.1016/j.msec.2006.05.019

[2] *Electrospun Nanofibers for Energy and Environmental Applications* [online]. nedatováno [vid. 2022-09-01]. Available from: https://link.springer.com/book/10.1007/978-3-642-54160-5

[3] BENDKOWSKA, W. Use of nanotechnology in the textile industry. *Przeglad Wlokienniczy*. 2003, no. 5, pp. 17–21. ISSN 1230-0381.

[4] KALAYCI, V., M. OUYANG a K. GRAHAM. Polymeric nanofibres in high efficiency filtration applications. *Filtration*. 2006, vol. 6, no. 4, pp. 286–293. ISSN 1479-0602.

[5] DEMIR, A., B. ACIKABAK a Z. AHAN. Development of Carbon Nanofiber Yarns by Electrospinning. *IOP Conference Series: Materials Science and Engineering* [online]. 2018, vol. 460, no. 1, 012027. ISSN 1757-899X. Available from: https://doi.org/10.1088/1757-899X/460/1/012027

[6] POKORNY, P., L. KOCIS, J. CHVOJKA, D. LUKAS, J. BERAN, M. BILEK a K. PEJCHAR. Alternating current electrospinning method for preparation of nanofibrous materials. In: *NANOCON 2013 - Conference Proceedings, 5th International Conference*. 2013, pp. 302–304. ISBN 978-80-87294-47-5.

[7] BALOGH, Attila, Richárd CSELKÓ, Balázs DÉMUTH, Geert VERRECK, Jürgen MENSCH, György MAROSI a Zsombor Kristóf NAGY. Alternating current electrospinning for preparation of fibrous drug delivery systems. *International Journal of Pharmaceutics* [online]. 2015, vol. 495, no. 1, pp. 75–80. ISSN 0378-5173. Available from: https://doi.org/10.1016/j.ijpharm.2015.08.069

[8] VALTERA, J., T. KALOUS, P. POKORNY, O. BATKA, M. BILEK, J. CHVOJKA, P. MIKES, E.K. KOSTAKOVA, P. ZABKA, J. ORNSTOVA, J. BERAN, A. STANISHEVSKY a D. LUKAS. Fabrication of dual-functional composite yarns with a nanofibrous envelope using high throughput AC needleless and collectorless electrospinning. *Scientific Reports* [online]. 2019, vol. 9, no. 1. Available from: https://doi.org/10.1038/s41598-019-38557-z

[9] MADHESWARAN, Divyabharathi, Šárka HAUZEROVÁ, Jan VALTERA, Maxim LISNENKO, Manikandan SIVAN, Ondřej BAŤKA, Věra JENČOVÁ, David LUKÁŠ, František JANDA a Eva KUŽELOVÁ KOŠŤÁKOVÁ. Braided threads with AC electrospun nanofibers for hygienic and medical applications - production and properties. In: *NANOCON 2021* [online]. 2021, pp. 252–257 [vid. 2022-09-05]. Available from: https://doi.org/10.37904/nanocon.2021.4355

[10] SHYNKARENKO, Andrii, Dekel AZULAY, Sarka HAUZEROVA, Andrea KLAPSTOVA, Michal MOUCKA, Vera JENCOVA a David LUKAS. *Fabrication of Micro/Nanofibrous Scaffolds using a Robotic Manipulator and Their Application for Tissue Engineering* [online]. 28 October 2021 [vid. 2021-10-28]. ISSN 2693-5015. Available from: https://doi.org/10.21203/rs.3.rs-112972/v1